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ANALYTICAL PREDICTION OF COLLAPSE OF RC PIERS INDUCED BY GEOMETRICAL NONLINEARITY

Rajesh P. Dhakal, and Koichi Maekawa
Dept of Civil Engg, The University of Tokyo, Hongo 7-3-1, Tokyo 113-8656, Japan
dhakal@concrete.t.u-tokyo.ac.jp, maekawa@concrete.t.u-tokyo.ac.jp

Abstract

To avoid complete collapse of structure and to protect human lives during earthquake, sufficient ductility is required. To achieve the aforementioned goal, structures are designed to fail in flexure. It is believed that such structures can undergo large ductility without brittle shear failure. If a RC pier designed to avoid shear failure is subjected to a major earthquake, the residual deformation becomes considerably high and P-delta effect due to the weight of superstructure and self-weight may govern the stability of the pier. This study analytically investigates the possibility of collapse of reinforced concrete piers accompanying the instability due to geometrical nonlinearity.

Introduction

The main aim of each seismic design code is to furnish recommendations so that the designed structures can avoid catastrophic failure. In doing so, usual practice is to design the structure to fail in flexure by ensuring higher shear capacity. However, a conceptual variation exists in different codes regarding the assessment of shear capacity. For example, unlike other codes, the degradation of shear contribution of concrete in inelastic range is not incorporated in JSCE seismic design code [JSCE, 1996]. It makes the designed structures liable to post-yielding shear failure. Nevertheless, it can be completely ruled out if either a large safety factor is considered [Okamura and Kim, 2000] or the contribution of concrete in the overall shear capacity is partly or fully overlooked, as in some other design codes [Tanabe, 1999]. In flexural RC piers, large deformation without shear failure can be expected during ground motion. In such situation, the overturning moment due to the overlying weight might become critical and govern the stability of the pier.

Figure 1 illustrates the equilibrium-based computation of lateral restoring force Q for a RC pier with height H under axial compression P and subjected to lateral displacement $\boldsymbol{d}$, where M is the moment capacity of the section computed as per the section analysis. As can be seen in figure 1, the bending capacity in the post-yielding inelastic region slowly decreases due to the compression softening of concrete. The capacity is further reduced because the cover concrete loses its load-carrying capacity due to spalling and average compressive stress of reinforcement decreases due to buckling. In very high deformation range, this behavior is further accelerated due to the rupture of reinforcement. Furthermore, it can be noticed in the figure that if the overturning moment induced by P-delta effect becomes equal to the sectional bending capacity corresponding to the current damage level, the lateral restoring force becomes zero. If the displacement is further increased, the restoring force becomes negative and a support from the opposite side is needed to maintain the stability of the pier; i.e. to avoid collapse induced by geometrical nonlinearity.

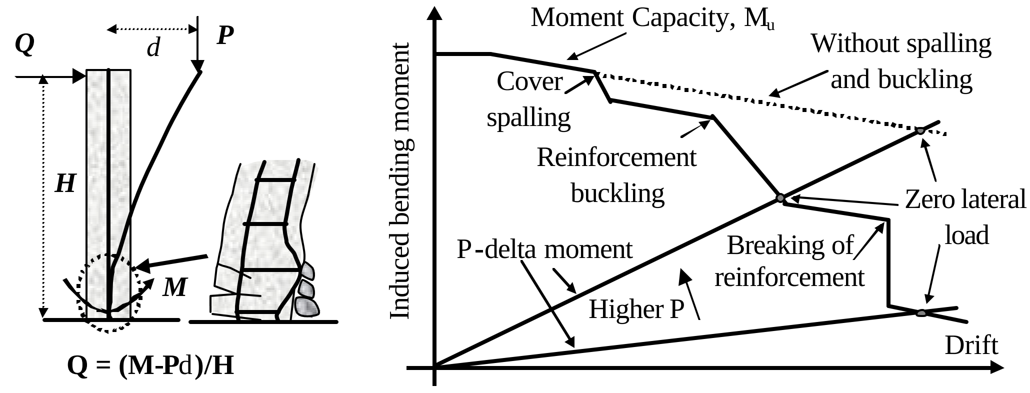

Figure 1 Bending capacity in inelastic range and effect of P-delta moment

Most of the design codes either do not realize or neglect the aforementioned effect of geometrical nonlinearity in limiting the ductility of designed structure. For example, JSCE code states that ductility equal to 10 can be ensured without any possibility of collapse if the shear capacity is at least double of the bending capacity. It can be argued that a possibility of flexural instability in highly ductile piers cannot be ruled out and the effect of geometrical nonlinearity should be assessed before deciding the allowable ductility. In this report, analytical investigation is carried out to corroborate the existence of flexural instability and also to explain the involved mechanisms.

Analytical Models and Verification

For the prediction of flexural instability of RC piers, frame analysis based on fiber technique [Menegotto and Pinto, 1973] is carried out in this study. A 3-D FEM analysis code COM3 [Maekawa et al., 1996], developed in The University of Tokyo, is used for the analytical investigation. As we are mainly concerned with the flexural behavior of columns with higher shear capacity, it is fairly assumed that the linear shear assumption adopted in the formulation will not have much influence on the predicted results. The stress-strain relationships for the constituent materials used in fiber analysis are schematically represented in figure 2. These material models consist of completely path-dependent constitutive equations including reinforcement buckling and cover spalling [Okamura and Maekawa, 1991; Dhakal and Maekawa, 1999].

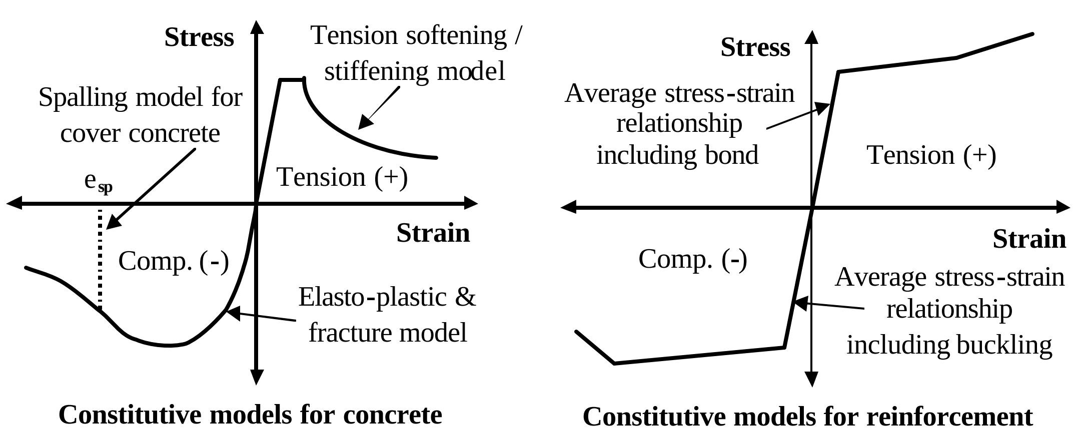

Figure 2 Schematic representation of constitutive models used in fiber analysis

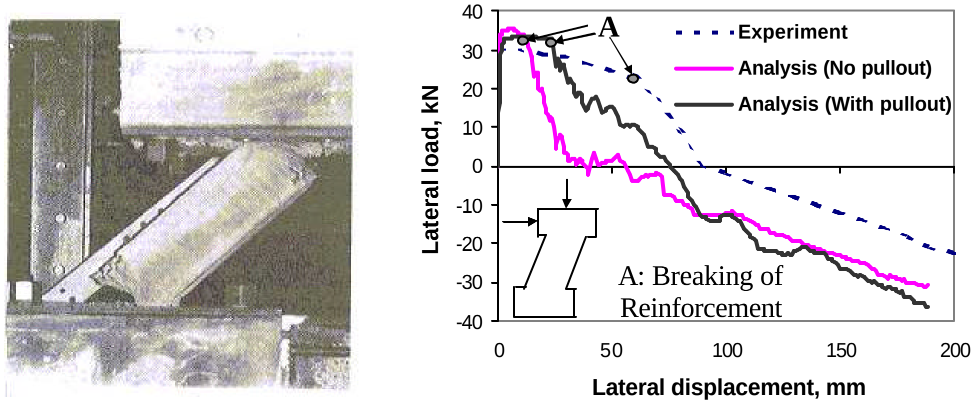

Figure 3 Analytical simulation of collapse test [Takiguchi et al., 1999]

To investigate the applicability of these analytical models for flexural columns in high-displacement range, collapse test of a small-scale RC column [Takiguchi et al., 1999] is simulated. The RC column is 30cm high with 10×10cm cross-section and is subjected to 51kN axial compression of 51kN, which is 9.4% of the axial capacity given the compressive strength of concrete is 54.2Mpa. Four 6mm-diameter normal strength bars (f_y=374Mpa) with 4mm clear cover are used as main reinforcement and 3mm-diameter high strength bars (f_y=653Mpa) at the spacing of 15mm are used as lateral ties. As can be seen in figure 3, the analytical result considering reinforcement pullout at the column-footing joint is fairly close to the experimental one. The analysis could satisfactorily capture the negative restoring force, as observed in the experiment. Nevertheless, the maximum load in the analysis is slightly larger and the displacement, at which lateral load becomes zero, is slightly less than in experiment. This is because the top of the column is fixed in the analysis, whereas it is reported that small rotation might have taken place in the experiment.

Analytical Results and Discussions

Effect of Nonlinearity in Post-Peak Response

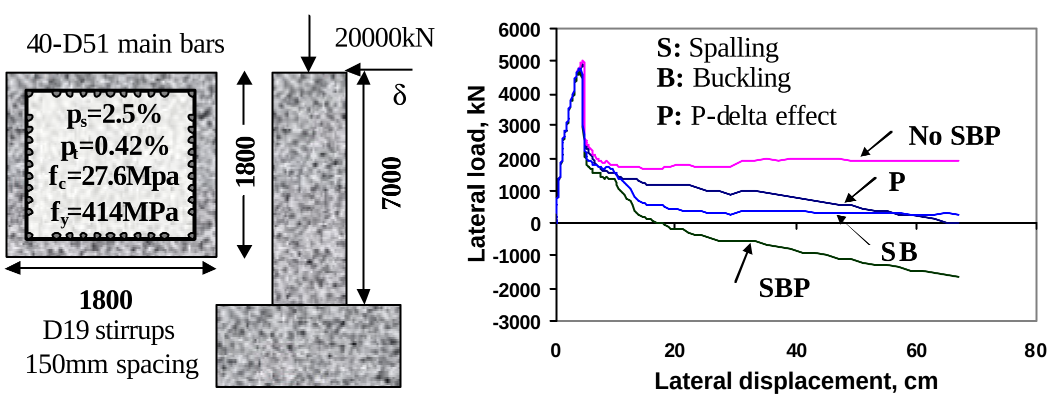

Figure 4 Effect of nonlinearities in post-peak flexural response

In order to assess the probability of flexural instability, a real size bridge-pier as shown in figure 4 is analytically investigated. Although this pier was designed

[Tanabe, 1999] for axial compression of 7000kN, larger value (200000kN) is assumed here to highlight the effect of geometrical and local nonlinearity. According to JSCE seismic design code, failure mode was ensured to be flexure. The load-displacement relationships obtained from pushover analyses are presented in figure 4 and these results are compatible with the mechanisms explained in figure 1. It can be observed that the flexural capacity significantly decreases in high displacement range due to spalling as well as buckling and the resisting force cannot become negative if P-delta effect is not considered in the analysis. As explained earlier, lateral load becomes zero when the overturning moment due to the P-delta effect is equal to the flexural capacity of the section at that damage level. Hence, if the lateral displacement is increased beyond this critical point, predicted lateral load becomes negative.

Analytical Investigation of Flexural Instability

To understand the physical consequences of negative lateral restoring force, two more detail analyses are performed. First, the monotonic displacement is applied at the top of the pier until the desired displacement level is achieved. Fiber analysis is carried out and the fiber strains, stresses and path dependent parameters at the last loading step are stored. Next, the lateral load at the top is released and the pier is subjected to its dead load and the weight of the superstructure only. The path dependent parameters stored in the previous run are used as the initial conditions for this analysis. In the second run, dynamic fiber analysis is performed with zero ground accelerations in X and Y directions in horizontal plane and acceleration equivalent to gravity is applied in the vertical direction to account for the effect of dead loads. To simulate the inertia force, the superstructure is modeled as a concentrated mass instead of a constant axial load at the top of the pier. Two sets of analyses, in which the second stage loading starts at displacements respectively smaller and larger than the critical displacement corresponding to zero lateral load (points A and B in figure 5), are discussed here. The analytical results are also illustrated in figure 5.

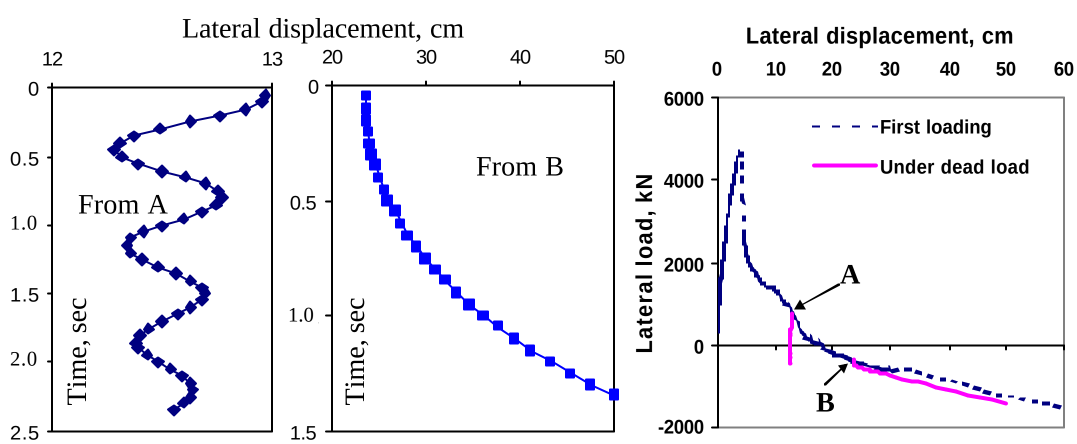

Figure 5 Response of RC pier under dead load in high displacement range

Some interesting behaviors could be discovered through these analyses. When the pier is allowed to deform freely at a displacement (A) smaller than the critical displacement, it undergoes free vibration and the pier attains a stable state with some residual displacement after some time. In contrast, if the pier is allowed to deform freely at a displacement (B) larger than the critical displacement, the lateral displacement keeps on increasing with time, indicating that the pier is unstable. These analytical results give ample evidence that RC piers under significant axial load can collapse if the residual displacement after an earthquake is higher than critical displacement.

Effect of Axial Load and Reinforcement Ratio in Critical Displacement

The critical displacement at which the lateral load becomes zero, is governed by the section bending capacity and the overturning moment due to P-delta effect. Hence, the amount of axial load and reinforcement in the section are among the most crucial parameters that affect the value of critical displacement. Here, a parametric analysis is performed with different axial loads and reinforcement ratio.

First, the aforementioned pier is analyzed with different levels of axial load ranging from 0 to 22% of the axial capacity. The analytical load-displacement relationships are shown in figure 6. As expected, the pre-peak stiffness and peak load slightly increase with increase in the axial load. When axial load is increased, higher uniform compressive strain is developed throughout the cross-section and tensile mechanisms like cracking, yielding and breaking of reinforcement are delayed. In contrast, compression inelastic mechanisms such as compression softening, cover spalling and reinforcement buckling occur earlier and the post-peak softening phenomenon becomes more prominent with increase in axial load. Consequently, the critical displacement, after which the pier becomes unstable, also decreases. Hence, the flexural instability might become predominant in case of high RC piers with significant self-weight and heavy overlying top mass.

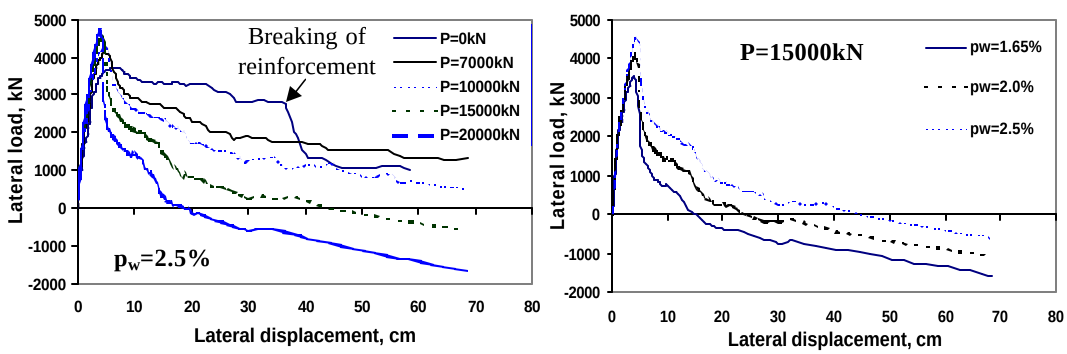

Figure 6 Effect of axial load and reinforcement ratio in flexural stability

It is obvious that reduction in the amount of main reinforcement decreases the bending capacity whereas the shear capacity is nearly unaffected. Consequently, the shear to bending capacity ratio increases and according to the current JSCE seismic design code, it can be argued that the possibility of collapse decreases and higher ductility can be ensured. But, can a reinforced concrete pier with small amount of main reinforcement maintain stability in high deformation range? To answer this question, the aforementioned pier, subjected to an axial load of 150000kN, is analyzed with different reinforcement ratio and the results are presented in figure 6. As expected, the peak load and the yielding displacement become smaller with decrease in reinforcement ratio. It can be noticed that the post-peak softening is also influenced by the reinforcement ratio. Interestingly, it was observed that a small decrease in reinforcement ratio causes significant reduction of the critical displacement. Hence, in spite of the fact that shear collapse can be avoided by reducing the amount of main reinforcement, such structures are liable to earlier collapse due to flexural instability.

Conclusions

Through analytical investigation, the existence of collapse mechanism even in flexure, led by instability due to geometrical nonlinearity associated with high axial load, is proved. Combination of degradation of section capacity in inelastic range and the overturning moment due to P-delta effect, the lateral restoring force decreases in large deformation range. At a critical displacement, when the overturning moment equals the residual section capacity, the lateral load becomes equal to zero. If the pier is subjected to higher displacement, a support from the opposite side is necessary to maintain the stability and to avoid collapse. The parametric study revealed that this behavior is accelerated by local nonlinearities such as cover concrete spalling and reinforcement buckling and the range of lateral displacement, throughout which the structure is stable, decreases with increase in axial load and decrease in the amount of longitudinal reinforcement. Hence, it is highly recommended that geometrical and local nonlinearity be considered either explicitly or implicitly in deciding the allowable ductility of RC piers with heavier top mass.

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